Engineering Case Library

ECL 76

PRECISION INSTRUMENT COMPANY

Modification of a Portable Video and

Broadband Instrumentation Recorder

Early in the summer of 1966, Mr. Stewart Smith, the chief engineer at the Precision Instrument Company of Palo Alto, California, received a memo from the head of the company's marketing division which told him that the division's marketing research[1] indicated that it would be profitable for the company to develop a more flexible version of its model PI-7100 video tape recorder (Exhibit 1). Advertising literature described the model 7100 recorder as a portable[2] machine, but it was able to operate only on conventional 60 cycle house current. Market research indicated, however, that there would be a substantial market for a recorder that was portable yet could be operated from "any available power source". Mr. Smith assigned a team of four engineers to work out the details of modifying the existing a.c. machine. Mr. Manchi Colah, a graduate of the University of London and, more recently, Stanford University, was one of the members of this team. By October 1966 something had been done and now Manchi was asking himself how to select a d.c. motor to replace the capstan a.c. (tape driving) motor in the machine.

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[1] marketing research -- among other things, research undertaken by the company to find out who will buy a product and how much they are willing to pay for it.

[2] portable in the sense that it is compact (less than 2 cubic feet in volume), operable in any position, operable outdoors under normal weather conditions (even light rain), and comparatively lightweight (weighing approximately 90 lbs.).

Prepared in the Design Division of the Mechanical Engineering Department by William J. Clemens under the direction of Karl H. Vesper with financial support from the National Science Foundation.

The Existing Recorder

The main difference between a typical home tape recorder and a video recorder like the PI-7100 is that the latter must handle much higher frequencies. To do so requires faster relative movement between tape and recording head (roughly 1000 inches per second versus 7 1/2 inches per second for a home audio recorder). Rather than driving tape past the head at such high velocities, as would be necessary on a home recorder, video recorders use a rotating recording head and, in effect, move the head past the tape at a very high speed. The PI-7100 passes tape helically around a semi-cylindrical assembly inside of which the recording head (scanner) rotates at speeds up to 2500 rpm (see Exhibit 2).

As shown in Exhibit 2, tape on the PI-7100 is threaded around an "input idler wheel", past the "audio recording head", between the capstan and a "pinch roller", helically around the tape head "scanner assembly", between the capstan and a second "pinch roller", then around the "output idler wheel" and onto the takeup reel. Driving force is provided by the three inch circumference steel capstan. A solenoid forces the two pinch rollers against the capstan to prevent the tape from slipping. A motor drives the capstan which drives the tape and thereby governs tape speed through the machine, its own speed being kept constant by a "servo loop"[3] in the recorder's circuitry. This motor must be powerful enough to pull tape off the supply reel and around the scanner assembly, as well as to replace energy dissipated by the distortion of the two rubber pinch rollers.

The Assignment

"I had nearly finished my part on the design of a digital tape recorder," said Manchi, "when our Chief Engineer, Stewart Smith, asked me if I would go over and lend a hand on the video tape recorder project that was just starting. Bill Rumple, the Project Engineer (team leader and coordinator) for this job, gave me a rundown on what was needed and what my part was on the team. He told me this new recorder was going to be a modification of the existing PI-7100, but would have to operate off of 'any available power source', which he said meant it would have to run off a.c. current that varied from the European standard 50 cps to the 400 cps commonly used in aircraft auxiliary generators. Our

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3 "servo loop" -- an electronic circuit which may be used to control the output of a machine by "feeding back" signals (either electrical or mechanical) from the machine's output to its input. A good example of a very simple "servo loop" is the thermostat temperature control circuit in a house. Here the output can be considered to be the amount of heat the furnace puts into the house. The thermostat measures the system's output (which is related to the temperature) and feeds a signal back to the furnace telling it to turn on or off.

team decided that the easiest solution would be to provide a rectifier to convert the incoming a.c. power to d.c. power, then operate the machine off d.c. Bill asked me to select some d.c. motors for the tape reels and capstan to see that they were properly "servoed" (i.e., to see that there were enough controls in the recorder to keep the motor speeds or torques constant).

Manchi thought he could perhaps use smaller motors on the new machine than in the 7100 recorder. The existing motors cost about $100 each, and he thought there might be a substantial saving in production costs if he used the least powerful motors possible. Since it wasn't obvious whether he could reduce motor size in the new machine, Manchi had to determine whether the PI-7100 had power to spare. For the capstan motor in particular, this involved finding how much torque was needed to drive tape through the machine.

Manchi Colah's Approach

Manchi believed that in modifying the 7100 tape tension and energy losses in the pinch rollers would not be altered. Consequently, he felt there were two ways to determine the torque requirements for the replacement motor. He could either calculate the tape friction drag from theoretical considerations, or, since the old recorder was readily available, he could run tape through the machine and calculate torque put out by the a.c. motor from measurements of its "input-output characteristics" (current, voltage, and input power).

"From what I knew about the recorder," Manchi recalled, "it wasn't clear which of these two methods I should use. I didn't know how to determine theoretically the energy lost in the rollers, so, at first glance, it seemed easier to look for a way to measure the output torque of the 7100's a.c. motor. I found out that this motor was an a.c. hysteresis synchronous motor which is often used whenever precise speed control is needed. I had never before determined the output torque of this kind by measuring its input-output characteristics, but I had a test on electrical machinery (Fitzgerald and Kingsley, "Electrical Machinery") to help me out. It said in an a.c. hysteresis synchronous motor, torque put out by the motor is proportional to the phase angle between the stator[4] magnetomotive force (mmf) vector and the rotor's[5] induced magnetomotive force vector. I thought it would be hard to measure these phase angles accurately. Even if I was able to measure them correctly, I would only be finding the torque delivered to the rotor, not the torque put out after all the frictional losses in the bearings were taken care of. Because of the apparent complications in this approach, I thought I'd have another look at the model 7100 recorder before choosing a method to find output torque."

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[4] stator -- the stationary winding of an electric motor.

[5] rotor -- the spinning magnet or winding of an electric motor.

Gathering Information

"After I took the back off the recorder," Manchi continued, "I found a d.c. motor (Exhibit 3) mechanically connected to the a.c. motor that normally drives the capstan. It was evidently supplied to drive the capstan for slow recorder scanning speeds.

"This made my job a lot easier because I recognized that I could now use this d.c. motor to find the torque required for driving the capstan. There is a linear current to torque relationship for a d.c. motor, so all I had to do to find output torque was to measure the current going through the motor with an ammeter."

While examining the inside of the recorder, Manchi noticed that although the a.c. capstan motor was directly connected to the capstan rollers, the existing d.c. motor was connected to these rollers indirectly, going through a 24:1 gear reducer which in turn was connected to the main shaft of the a.c. motor. Because of friction in the reducer and the a.c. motor, Manchi reasoned that some of the d.c. motor power would be lost before it reached the capstan rollers. Assuming that power losses through the d.c. motor drive train were the same whether the tape was running through the recorder or not, he decided that the capstan torque needed could be computed as follows:

  (d.c. motor torque needed to drive tape through the machine)
- (torque needed to drive the gear reducer)
- (torque needed to drive a.c. motor)
= (torque needed to drive the capstan).

First Experimental Measurement

Accordingly, Manchi, while running the tape at a standard speed of 8.5 ips, used an ammeter to measure the imput current to the d.c. motor: 1) with the magnetic tape running through the machine; 2) without the tape running through the machine, but with the pinch rollers still operating; and 3) with neither the tape nor the pinch rollers on the machine. He asked his friends who had been working on the new recorder with him if they had any information on the present d.c. motor that could be used to convert his electric current data into units of torque. One of them had copied in his notebook from a manufacturer's catalogue the torque constant for this motor (k=13.6 in-oz/amp). By subtracting one current reading from another (value obtained in run 3 from the value obtained in run 1 and the value obtained in run 3 from the value obtained in run 2) then multiplying the resultant values by the torque constant, k, Manchi computed the following quantities (Exhibit 4):

$$T_{\text{tape+rollers}} = 15 \text{ in-oz}$$

$$T_{\text{rollers}} = 5 \text{ in-oz}$$

where $T_{\text{tape+rollers}}$ is the maximum torque needed to drive tape through the machine, and T_{rollers} is the torque required just to drive the rollers (no tape in the machine).

"I felt that the results were reasonable," said Manchi, "but decided it would be worth-while to check them with results from a theoretical analysis. I have found that when you have more than one method by which you can solve a problem, which doesn't often seem to be the case, it is a good idea to check your answers by trying to get the same results different ways. If you find that one answer is much different from the other, then you had better find where you went wrong. Finding a mistake before the design goes to the lab for testing can save you a lot of trouble in revising a faulty piece of equipment later."

Cross Check of Results

For his alternate calculation, Manchi thought he would assume takeup[6] tension in the tape was negligible, and concentrated on finding the maximum holdback[7] tension in the tape. By adding this force to the drag force from the tape traveling around the tape scanner (which he would determine theoretically), Manchi hoped to find the force necessary to drive the tape through the recorder. "I found that someone who had worked on our sample 7100 recorder before me had calibrated a potentiometer which was connected to supply reel motor so that it could be set for any holdback tension desired," Manchi explained. "I set the potentiometer at about the middle of its dial and found the maximum holdback tension for that setting was 7 oz. By adding this to the force needed to overcome friction drag of the tape around the scanner, I could calculate the torque needed to drive the tape through the machine. Since I didn't know how to compute energy losses in the rollers, I thought I would use the 5 in-oz figure from my experimental analysis to account for these losses. This 5 in-oz term plus the torque needed to take tape off the supply reel and around the scanner assembly should then be the minimum pull needed from the motor."

From a previous project Manchi recalled a formula he thought he would use for computing tape tension at the capstan. This formula was:

$$T_2 = T_1 e^{\mu\theta} \quad [8]$$

where T_2 is the tape tension at the capstan, T_1 is the tape holdback tension, e is the base of the natural logarithms, μ is the coefficient of friction for Mylar tape slipping on steel ($\mu = 0.2$), and θ is the total wrap angle of the tape. Next Manchi felt he should compute the torque and compare it to his earlier result. Beyond that, he expected there would be questions of whether this agreement was close enough, what to do if it was not, or how to go about selecting a motor if it was.

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[6] "takeup tension" -- tension in the tape between capstan and takeup reel.

[7] "holdback tension" -- tension in the tape between capstan and supply reel.

[8] A derivation of this formula is presented in Exhibit 5.

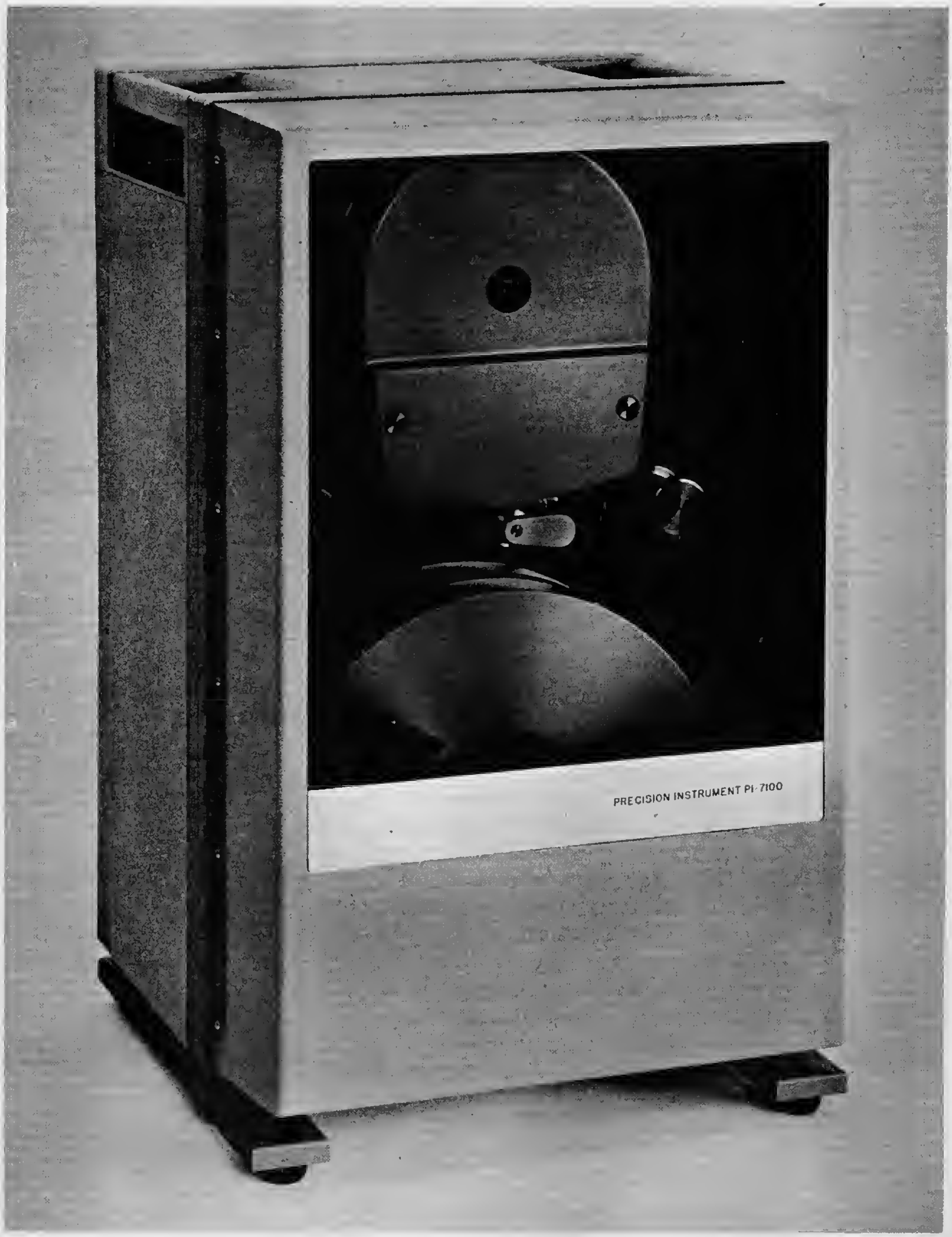


Exhibit 1. Precision Instrument Company Model PI-7100 Video Tape Recorder --cover closed. (continued on next page)

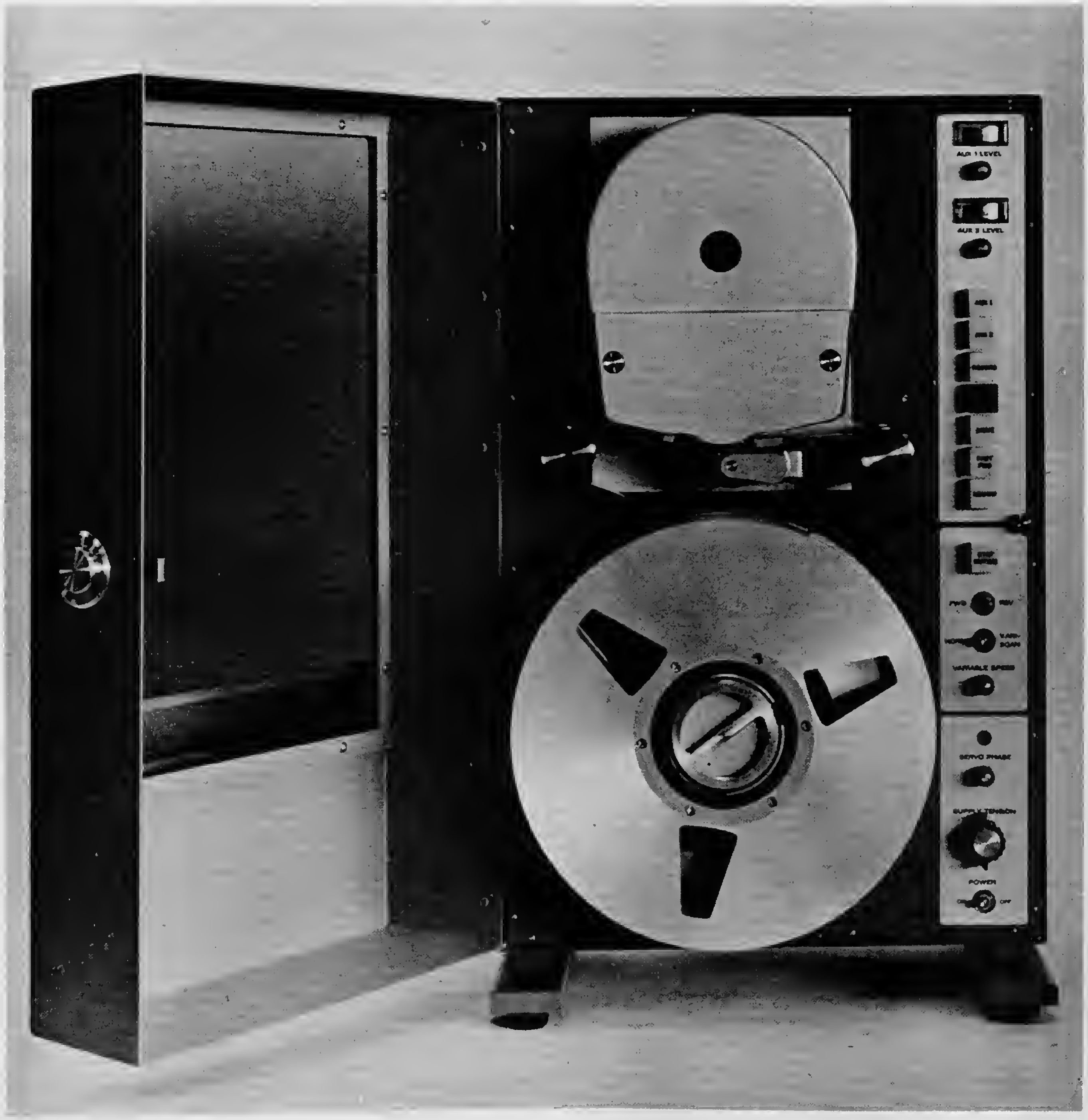


Exhibit 1 (continued). PI-7100 Video Tape Recorder (cover open).

1. DESCRIPTION AND SPECIFICATIONS

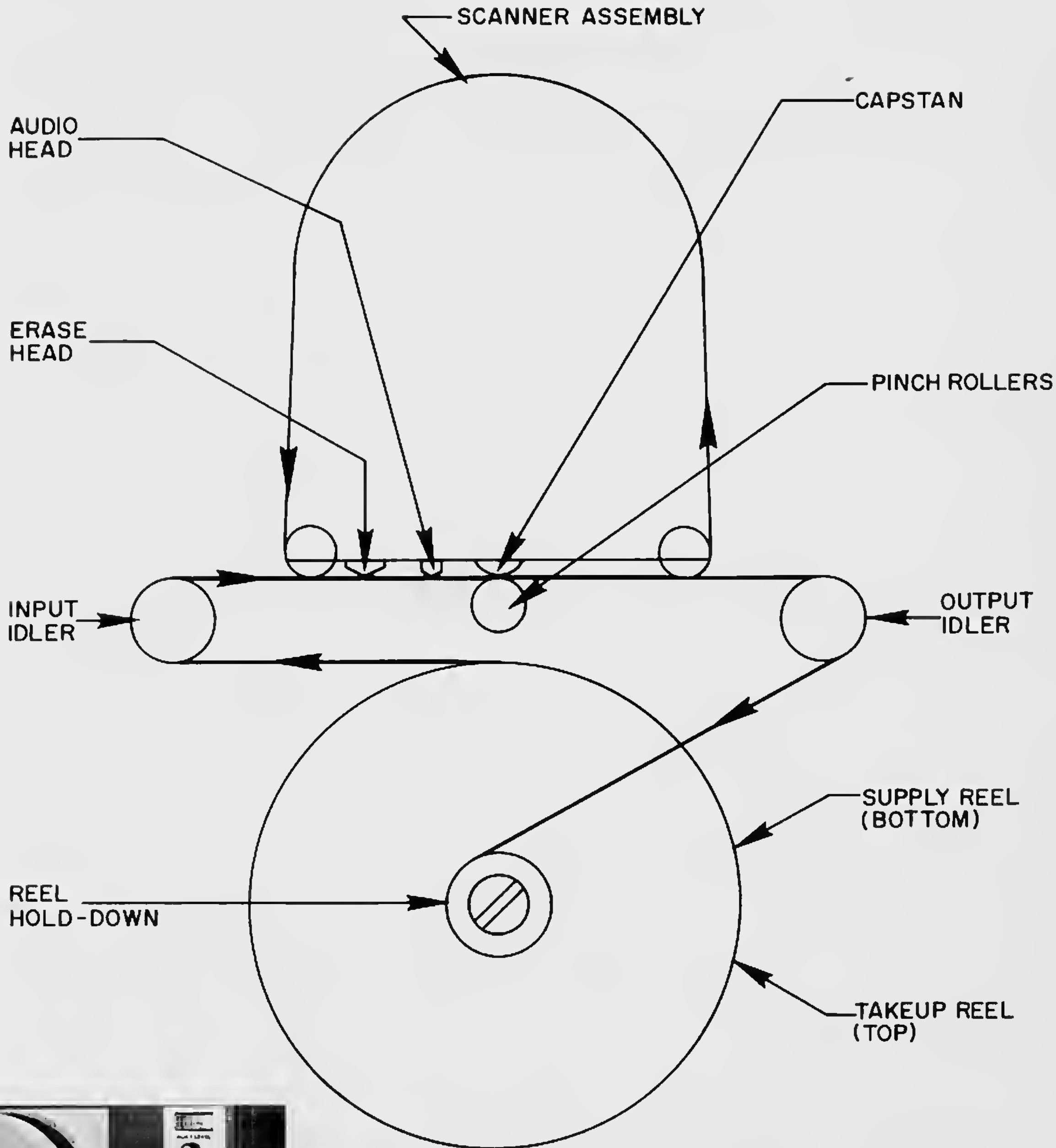
1.1 DESCRIPTION

The Precision Instrument Model PI-7100 Portable Video and Broadband Instrumentation Recorder may be used for recording both picture and sound in closed-circuit television (CCTV) applications or instrumentation data from nonsynchronous sources.

Installed in its weatherproof case the recorder/reproducer will perform efficiently in modern environments which are not harmful to operating personnel. The PI-7100 will record at either of two speeds (7.5 and 8.46 ips) and playback at either speed. In addition, two special functions are provided (1) Stopscan, (2) Variscan. Stopscan is a single pushbutton control to allow for the viewing of one single field while tape motion is halted. Variscan is a variable control which allows for playback at any speed between 0 and 16 ips; however, the original recording speed must use 8.46 ips.

The PI-7100 is completely transistorized and with the stacked reel design, makes a very compact recorder/reproducer.

All operating controls are accessible on the front panel and are marked to identify individual functions. The PI-7100 may be operated locally or from a remote location, selectable by a switch on the input panel.



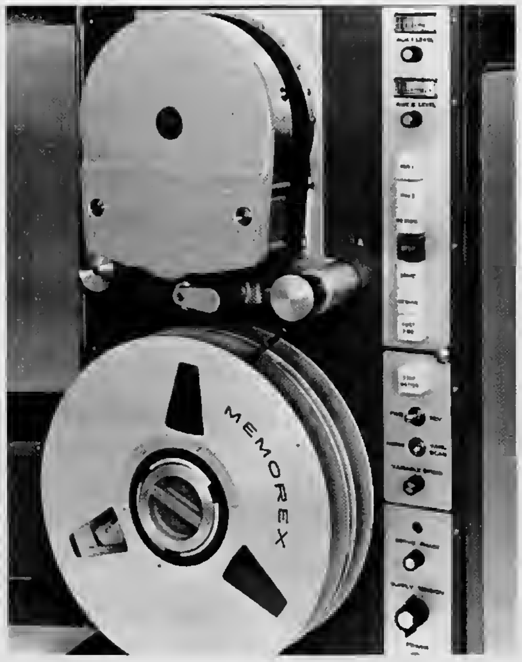
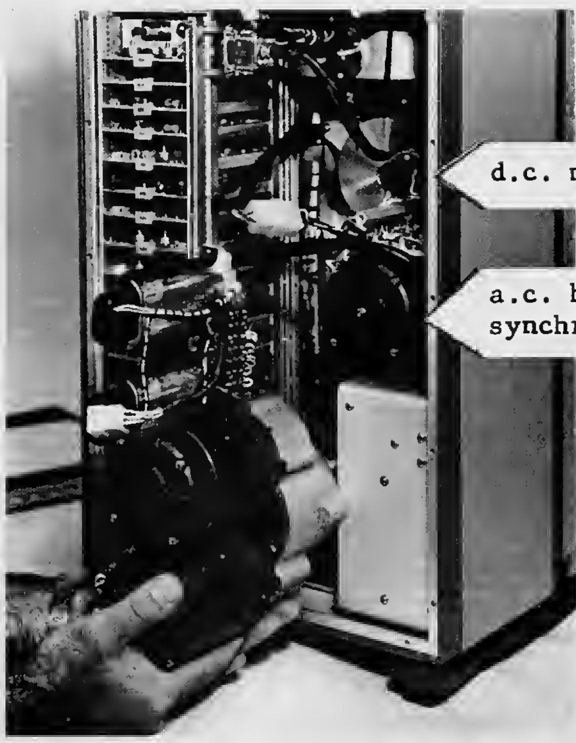


Exhibit 2. Simplified Drawing Showing Path of Tape Around Scanner Assembly. Insert is Photograph of Tape Threaded on Recorder.

a. Reel drive connector being disconnected.



b. Reel drive assembly being removed.

Exhibit 3. Two Views of the Back of the PI-7100 Recorder Showing the Capstan Drive Motors.

17 OCT 1966

VIDEO Machine

Estimate of current and torque on the capstan motor:

There is a slow motion D.C. motor which drives the capstan thro' a gear ratio and the Hyd. synchr motor.

This was used to check torques Ratio is 24:1

Torque constant → 13·6 in oz/amp

With 10 oz of holdback at empty reels,

→ 155 mA current at $8\frac{1}{2}$ IPS capstan speed with tape & pinch roller holdback was $\left(10 \times \frac{5{\cdot}25 - 1{\cdot}4375}{5{\cdot}25}\right)$ oz = 7·26 oz

→ 124 mA at $8\frac{1}{2}$ IPS and with P. Rollers in but no tape

∴ 31 mA nett to run tape:

$\cdot031 \times 13{\cdot}6 \times 24 =$ 10 in oz FOR TAPE

→ No PINCH ROLLERS No TAPE → 108 mA → VERIFIED TWICE

So ·016 mA for P.Rollers → $\cdot016 \times 13{\cdot}6 \times 24 = 5$ in oz

Total = 15 in oz for tape + rollers

Repeated Test

→ ·240 mA for holdback of $\left(16\text{ oz} \times \frac{2{\cdot}25\ \cancel{5{\cdot}25-1{\cdot}5}}{5{\cdot}25-1{\cdot}5}\right)$ oz

FOR TAPE + PIN. ROLLERS.

and ·230 for holdback of $6\text{ oz} \times \frac{2{\cdot}25}{3{\cdot}75}$ ‖ 6.52 oz

Exhibit 4. A Page From Manchi Colah's Notebook Showing Some of his Calculations on the new Video Recorder. The Typewritten Notes Refer to the Casewriter's Notes on the Next Page.

EXHIBIT 4 (continued)

Casewriter's notes on Manchi Colah's calculations.

1. The"roller holdback" calculation here was not essential for determination of the d.c. slow-scan motor output, but was necessary if Manchi ever decided to do a theoretical analysis of the torque needed to drive tape through the recorder. The reel motor was a constant torque device that could be set for any torque desired. It had been calibrated so that the empty reel holdback tension was adjustable. Manchi set this tension for 10 oz. on his first set of tests. In his "roller holdback" calculation, 5.25 inches is the outside diameter of the tape reel, 2.25 inches is the inside diameter of the tape reel, and 1.4375 inches is the distance from the outside edge of the reel to the tape. His calculation here is wrong, but he used the correct relationship on his "repeated test" (4). In this step (1) Manchi found that it took 155 m.a. of current to drive both the tape and the pinch rollers with the d.c. motor.

2. Manchi discovered that it took 124 m.a. of current to drive just the pinch rollers. By subtracting 124 m.a. from 155 m.a. and multiplying the difference by the torque constant (13.6 in. - oz./amp) and the gear ratio (24:1), he found the torque needed to drive just the tape was 10 in.-oz.

3. Manchi took the pinch rollers off the machine and found it took 108 m.a. to drive just the capstan roller. By subtracting 108 m.a. from 124 m.a. and repeating the calculations in 2, Manchi found the torque needed to compensate for the losses in the pinch rollers was 5 in.-oz.

By adding 5 in.-oz. to 10 in.-oz., Manchi found the total torque needed to run the tape through machine was 15 in.-oz.

4. These were the current readings for Manchi's repeated test where he changed the empty reel holdback tension from 10 oz. to 16 oz.

EXHIBIT 5

Calculation of Friction "Drag" around a curved path.

The formula that Manchi chose to solve his problem with is only good for belts which are on the point of slipping on flat surfaces, but if a dynamic coefficient is used, it is equally good for belts slipping on flat surfaces. It can be most easily derived by summing forces acting on a differential portion of the round surface then integrating around the entire surface.

Referring to figure 1, T is the tension in the tape, dT is the change in tension in the tape over a distance ds, $d\gamma$ is the elemental angle subtended by ds, θ is the total wrap angle, R is the radius of curvature of the line ds, and μ is the coefficient of sliding friction between the tape and the support over which it rides.

Adding the forces in the y-direction and setting the resultant equal to zero,

$$N - (T + T + dT)\sin\left(\frac{d\theta}{2}\right) = 0$$

or

$$N = (2T + dT)\sin\left(\frac{d\theta}{2}\right)$$

Performing the same operation in the x direction,

$$(T + dT)\cos\left(\frac{d\theta}{2}\right) - T\cos\left(\frac{d\theta}{2}\right) - \underbrace{\mu N}_{\text{Friction force}} = (dT)\cos\left(\frac{d\theta}{2}\right) - \mu(2T + dT)\sin\left(\frac{d\theta}{2}\right) = 0$$

dropping second-order terms and making the approximation for small angles (which is valid because $d\gamma$ is small), i.e. $\sin(a) = a$, $\cos(a) = 1$ for (a) very small, we get the differential equation

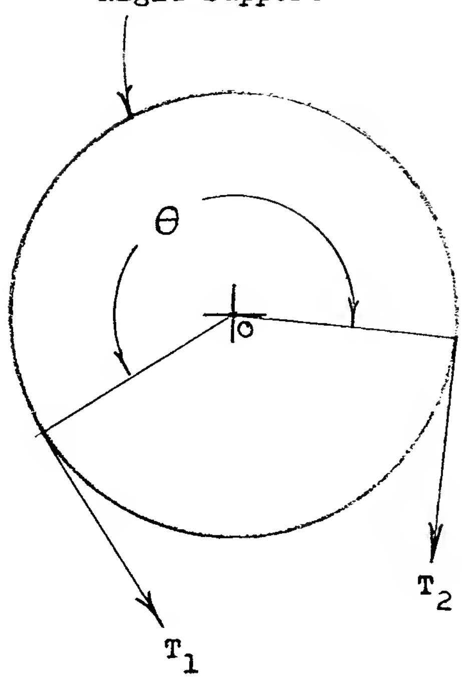
$$dT\cos\left(\frac{d\theta}{2}\right) = 2\mu T\sin\left(\frac{d\theta}{2}\right) + \mu dT\sin\left(\frac{d\theta}{2}\right) = dT(1) = 2\mu T\left(\frac{d\theta}{2}\right) + 0 .$$

$$\text{or } dT = \mu T d\theta$$

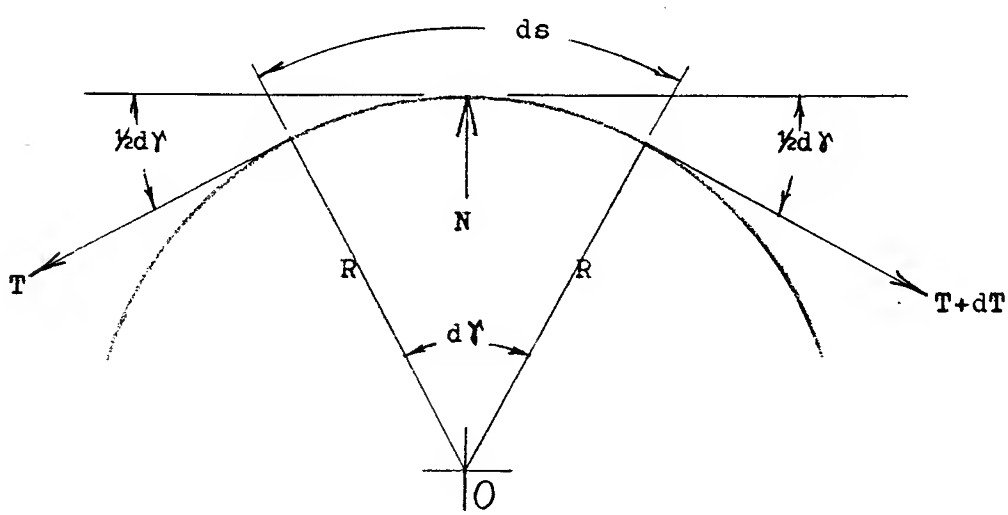
Transposing and integrating both sides of the equation between the limits $T = T_1$, $\gamma = 0$ and $T = T_2$, $\gamma = \theta$, the formula Manchi decided to use is obtained.

$$\int_{T_1}^{T_2} \frac{dT}{T} = \int_{0}^{\theta} \mu d\theta$$

which reduces to $\ell n T_2 - \ell n T_1 = \mu\theta$; or $T_2 = T_1 e^{\mu\theta}$



1a. General Figure



1b. Enlarged Section of 1a.

Figure 1.

PRECISION INSTRUMENT COMPANY (B)

Using a holdback tension of 7 ounces and a total wrap angle of 360° (2π radians), Manchi calculated the torque needed to pull the tape around the scanner assembly to be 17 in.-oz. (including the 5 in.-oz. torque needed to compensate for losses in the capstan rollers). "This figure agreed fairly closely with what I had found out experimentally," said Manchi, "so I started looking for a manufacturer to furnish our motors."

Manchi was looking at that time for someone to supply him with the d.c. motors for both the tape scanner and the capstan. "The scanner motor was the most demanding of the two motors. It had to have the best speed and vibration characteristics of any of the motors that we used, so we first looked for a manufacturer to furnish it, assuming that he would be able to supply the capstan motor too. The physical requirements of the two motors were about the same and the capstan motor was smaller than the scanner motor, so we thought this would be the simplest approach."

Manchi sat down with a couple of other engineers in a "bull session" to discuss what they should look for in a set of new motors. One of the engineers in the group had worked on the development of the 7100 recorder and his experience has given him a set of figures he thought should be included in the specifications for the new motors.

After they agreed on some preliminary specifications for the motors, Manchi sent out inquiries to about 35 different motor manufacturers asking them whether or not they had motors meeting the scanner motor specifications and, if so, if they would send him some literature on what was available. Manchi then called up these suppliers and asked them for more details on their products, e.g., prices, whether the motors were special orders or stock items, and if they could supply the number needed. "The catalogues the manufacturers send you do not convey a complete picture of what is currently available," explained Manchi. "To really find out the whole story you should study their catalogues then call them up and talk with them about their products." By this process, basing his decision primarily on cost and availability, Manchi narrowed down the field of suppliers to one out of the six that had responded affirmatively to his first letter.

Manchi then wrote this manufacturer to be sure he could also get the smaller capstan motor from him. He specified in his inquiry the size motor needed (load torque 15 in.-oz. at 240 rpm), shaft diameter (between 3/4" and 1"), effective shaft length (about 3"), maximum diameter of rotor (6") and total indicated runout (T.I.R.) (.001"). The manufacturer affirmed that he could supply a motor to meet these requirements. Soon after that, Manchi completed work on the servo-mechanism for the recorder and was transferred to another project, his job having been completed.

INSTRUCTOR'S NOTE

on Precision Instruments Case

This study is written primarily for lower division engineering students; in particular, students in freshman and sophomore orientation and statics courses.

The main text of the case attempts to show how an engineer went about solving one of the minor problems he ran across while working as part of a team of engineers on a larger project. It shows how he first received his problem, how he went about understanding it and how he eventually proceeded to solve it. The final steps of calculating the motor torque are left to the student, although the critical formula $T_2 = T_1 e^{\mu\theta}$ is given to him. A derivation of this formula is given in Exhibit 5 to give the student a chance to understand how it was arrived at. Finding the torque requirement of the motor required the student to understand how to calculate torque given a force (T_2) and its moment arm. The radius of the capstan roller is not given explicitly in the case, but the circumference of the roller is given in Exhibit 2, and the student should be able to calculate it from that. The circumference is not given just as an exercise for the student, but because that was the data given Mr. Colah when he approached the problem.

Some of the topics this case is intended to bring to the student's attention are: there is often more than one way to solve a problem and it is a good idea to solve it, if possible, by alternate methods; and sometimes it is difficult to apply theory to practice as in the case of measuring the output torque of the hysteresis motor from its input-output characteristics. There is also some general information included to expose the novice engineering student to some of the tools he will acquire later, such as phase plane analysis (phase angles), servo loops, etc.